# Currents in Rivers Observed by Spaceborne Along-Track InSAR – CuRiOSATI –

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## LONG-TERM GOALS

The long-term goal of this project is the establishment of receiving, processing, and interpretation capabilities for spaceborne along-track interferometric synthetic aperture radar (along-track InSAR, ATI) data at the University of Miami's Center for Southeastern Tropical Advanced Remote Sensing (CSTARS) for high-resolution surface current field mapping with special emphasis on applications in estuarine environments and rivers.

## OBJECTIVES

Within the project period of 24 months (now extended by another year, ending on December 31, 2011), we intended to

- acquire series of ATI images of selected test sites;
- implement ATI raw data processing capabilities at CSTARS;
- develop a robust current retrieval algorithm for rivers, which corrects the ATI-derived Doppler velocities for contributions of wave motions;
- compare the results with available reference data;
- evaluate the data quality in view of known user requirements; and
- evaluate the potential of dedicated ATI satellite missions with optimized instrument, platform, and orbit parameters for nearshore, estuarine, and river observations.

The main satellite to be used was TerraSAR-X, but we were optimistic to obtain additional ATI data from other satellites, such as TanDEM-X, RADARSAT-2, and the COSMO-SkyMed satellite constellation.

## APPROACH

The project consists of five main tasks, which are defined as follows.

# Report Documentation Page

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Task 1: Data Acquisition. Test sites of interest were to be selected, taking into account requirements of ONR and its existing programs, the suitability of the test sites for ATI data acquisitions and for the tests to be performed, and the availability of reference data for validation of the results. TerraSAR-X ATI images of the test sites were to be acquired repeatedly during a period of several months. At the beginning this was expected to be done in close collaboration with Hartmut Runge and Ulrich Steinbrecher at DLR Oberpfaffenhofen (Germany), who would order the experimental data products and program the instrument for the individual data acquisitions, respectively. At a later stage, the ordering of ATI data acquisitions with TerraSAR-X would be possible through the Web interface that is also used for ordering conventional data products by regular PIs of TerraSAR-X. Furthermore, CSTARS would build up its own data ordering system for TerraSAR-X and obtain direct access to the satellite in 2010. As a secondary activity, Task 1 includes the collection of reference data from in-situ measurements, numerical models, and existing data bases. It was planned to obtain such data from colleagues at other research institutions and agencies.

Task 2: Raw Data Processing. The ATI raw data need to be processed into complex SAR images, and some additional processing steps (co-registration etc.) need to be applied to obtain the phase images required for current retrievals. While this work was originally done by Steffen Suchandt at DLR Oberpfaffenhofen (Germany), we were planning to obtain his software for use at CSTARS in the course of this project. The project was expected to make a key contribution to the establishment of ATI data receiving and processing capabilities at CSTARS.

Task 3: Current Retrieval. The conversion of ATI phase images into actual line-of-sight current fields requires an application of advanced filtering techniques and a correction of detected Doppler velocities for contributions of wave motions and their spatial variations due to wave-current interaction, as theoretically discussed and partly demonstrated in previous publications [1][2][3]. The ATI-derived current fields from the Shuttle Radar Topography Mission (SRTM) in [2] and [3] were not corrected by this method because they were not absolutely calibrated, thus the mean contribution of wave motions could not be separated from other contributions that were not known theoretically. The mean bias of the detected velocities had to be corrected on the basis of boundary conditions that the flow field should satisfy along shorelines within the image. This workaround is not required for TerraSAR-X data, but some theoretical model and algorithm improvements were required for river applications, since the computation of spatially varying wave contributions to Doppler velocities is a different problem for a river than for open waters. We were planning to upgrade the existing numerical along-track InSAR model to account for shallow-water effects and boundary effects such as wave refraction, reflection, and dissipation at river banks. All filtering and correction of the ATI data and the development of model improvements was to be done by PI Roland Romeiser. In addition, an algorithm for direct wind retrievals from the amplitudes of TerraSAR-X SAR / ATI images was to be implemented to eliminate the need for wind data from external sources. This was to be done in collaboration with Jochen Horstmann of NURC, La Spezia (Italy).

Task 4: Evaluation. The ATI-derived surface current fields would be checked for consistency and compared with available reference data to determine the achievable data quality under varying conditions (wind speed / surface roughness, river width, angles between flow direction, wind direction, and radar look direction, etc.). Based on the results, the suitability of the method for various applications would be discussed, and the potential of dedicated spaceborne ATI missions with optimized instrument and orbit parameters for ocean and river applications would be evaluated.

Task 5: Dissemination. The results obtained at different stages of the project were to be disseminated through a project website, periodic progress reports to ONR (such as this one), presentations at informal meetings as well as national and international conferences, and at least two publications in peer-reviewed journals. To ensure an efficient collaboration and data exchange with existing ONR program teams and other potential partners and users, we were planning to contact these colleagues in an early stage of the project and inform them about our objectives, plans, and needs.

**WORK COMPLETED**

Task 1: Data Acquisition. First TerraSAR-X ATI images of ocean and river scenes were acquired in Aperture Switching (AS) mode in spring and summer 2008, including six images of the Elbe river (Germany), which were made available to us in December 2008. In spring 2009, another set of images of the Elbe river was acquired in Dual Receive Antenna (DRA) mode. In Fall 2009, the acquisition of AS-mode images was continued. The Elbe river was selected as first test site a long time ago because we had experiences with it from the analysis of SRTM data [3] and it was easy to obtain additional reference data from (German) governmental agencies. After the Elbe river, the Lena river in Siberia was selected as a second river for routine data acquisitions during a longer period. The Lena river has strong seasonal variabilities in its runoff (minimum 1400 $m^3/s$ in April, maximum 74,000 $m^3/s$ in June), and it is covered with ice for several months in winter. Reference data are available from a station. In April and May 2010, a series of DRA-mode images was acquired over Skagit Bay (WA), Columbia River (OR / WA), St. Johns River (FL), Amazon (Brazil), and a few open-ocean test sites and other test sites. Receiving capabilities for TerraSAR-X, COSMO-SkyMed, and RADARSAT-2 at CSTARS were implemented as planned, but the existing generation of COSMO-SkyMed satellites does not have the ATI data acquisition capabilities that were discussed in some concept studies, thus we have not obtained ATI data from other satellites than TerraSAR-X. Proposals for some special ATI and combined ATI-XTI (along-track and cross-track interferometry) experiments with the newly available TerraSAR-X / TanDEM-X constellation (the TanDEM-X satellite was launched as a companion to TerraSAR-X in summer 2010) were submitted to DLR and are still waiting for approval while planned routine acquisitions with TanDEM-X have a higher priority during the first 1-2 years of the mission than experimental additional acquisitions.

Task 2: Raw Data Processing. The first six TerraSAR-X AS-mode images of the Elbe river were processed in December 2008. An analysis revealed some artifacts in the data that could be attributed to suboptimal processing parameters. Improved results were obtained in September 2009. The original processing of DRA-mode images from spring 2009 did not lead to satisfactory results, but improved procedures permitted current retrievals of quite high quality in spring 2010. Examples of results obtained in 2010 are shown at the end of this document. As of current planning, CSTARS will have capabilities to order, downlink, and process ATI imagery from TerraSAR-X (running in AS mode) at the end of 2011.

Task 3: Current Retrieval. Using the first six TerraSAR-X AS-mode images of the Elbe river, specific filtering and correction algorithms for TerraSAR-X data were developed. These algorithms can identify and eliminate phase signatures of ships and other strong scatterers in the water with nonrepresentative velocities, reduce the effect of azimuth ambiguities (ghost images of strong scatterers on land over water), correct the absolute phase calibration on the basis of phases measured over land, reduce remaining phase noise by filtering, convert, ATI phases into radial velocities, and correct the velocities for contributions of wave motions. Almost the same algorithms could be applied to the DRA-mode images from spring 2009 and spring 2010, but a continuous algorithm improvement

process is still ongoing and some procedures are getting more robust, more accurate, and / or more computationally efficient with almost every ATI image that gets processed. Some specific ATI model modifications for river applications have been implemented, but their quality and significance need to be tested with data from a variety of different test sites and current and wind conditions. The amount of ATI data available so far is still very limited.

Task 4: Evaluation. Aside from some uncertainties about the best choice of model settings for the correction of ATI data for contributions of wave motions, our latest results show good agreement between ATI-derived currents and reference currents and a quite consistent data quality for all images (and for different regions within each image). A final evaluation will be presented at the end of the project. Unfortunately, some of the DRA mode images acquired in 2010 are of much lower quality than we had hoped for, since the acquisitions were accidentally programmed (by someone at DLR) at HH instead of VV polarization, leading to a significantly worse signal-to-noise ratio. Due to this mistake, most of the DRA-mode data are worse in quality than corresponding AS-mode data; this should have been the other way around with DRA-mode data acquired correctly at VV polarization. This is very disappointing and frustrating for all PIs working with DRA mode data of ocean and river scenarios (not so much for land applications).

Task 5: Dissemination. The first TerraSAR-X results obtained in 2009 were presented in a press release of RSMAS and reproduced on several websites. A full peer-reviewed paper was accepted for publication in IEEE Trans. Geoscience Remote Sensing in August 2009 and published in February 2010 [4]. Furthermore, the early results were presented at *Oceans 2009* in Bremen, Germany [5], at the *2009 ONR Physical Oceanography Review Symposium* in Chicago, and at the *2009 International Geoscience and Remote Sensing Symposium (IGARSS)* in Cape Town, South Africa [6]. More results were presented at *Oceans From Space* in Venice, Italy [7], The *Living Planet Symposium* of the European Space Agency in Bergen, Norway [8]. and *IGARSS 2010* in Honolulu [9]. Another presentation was given at the TerraSAR-X Science Team Meeting in Oberpfaffenhofen, Germany, February 2011. In the fall of 2011, we are getting ready to finalize the analysis of several ATI images and to submit further manuscripts to journals such as IEEE Trans. Geoscience Remote Sensing.

## RESULTS

Some current fields (and ship speed results) obtained for Elbe river images are shown in Figs. 1-4. The data quality is good and consistent with our expectations. Some results from the 2010 DRA-mode campaign will published soon. We know now how to process and correct such data, and we will have complete ordering, receiving, and processing capabilities for TerraSAR-X ATI data at CSTARS at the end of 2011 (this took longer than expected due to complicated negotiations and slow software development / implementation efforts of our partners at DLR and InfoTerra in Germany). We will do current measurements by TerraSAR-X over some more rivers and coastal areas in the follow-on project SARprises, in which we would like to develop algorithms for deriving higher-level data products such as river runoff estimates and bathymetric maps of coastal waters. SARprises (N00014-11-1-0280) started in 2011 (see separate report).

## IMPACT/APPLICATIONS

Techniques for satellite-based current measurements in rivers and coastal areas are valuable for a variety of applications in oceanography, climate research, hydraulic engineering, drinking water and flood risk management, and other disciplines. For DoD operations, the navigability of rivers and the

monitoring and prediction of flooding events and changes in the water supply for major cities and agricultural regions are of interest. The use of satellite-based monitoring techniques is the most promising approach. In addition to currents, information on the speed of sea ice, ships, and land vehicles can be derived from ATI imagery.

## RELATED PROJECTS

The techniques developed here will be used for other ONR-funded projects, such as the DRI "Inlet and River Mouth Dynamics" in which we are involved, and the direct follow-on project SARprises (SAR product innovations and enhancements, N00014-11-1-0280). Plans for further ATI-based projects at RSMAS / CSTARS exist. The amount of ATI images acquired and processed by CSTARS will increase significantly in 2012, when the implementation of the complete ordering, downlinking, and processing software for TerraSAR-X AS-mode data has been completed.

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## PATENTS

None.

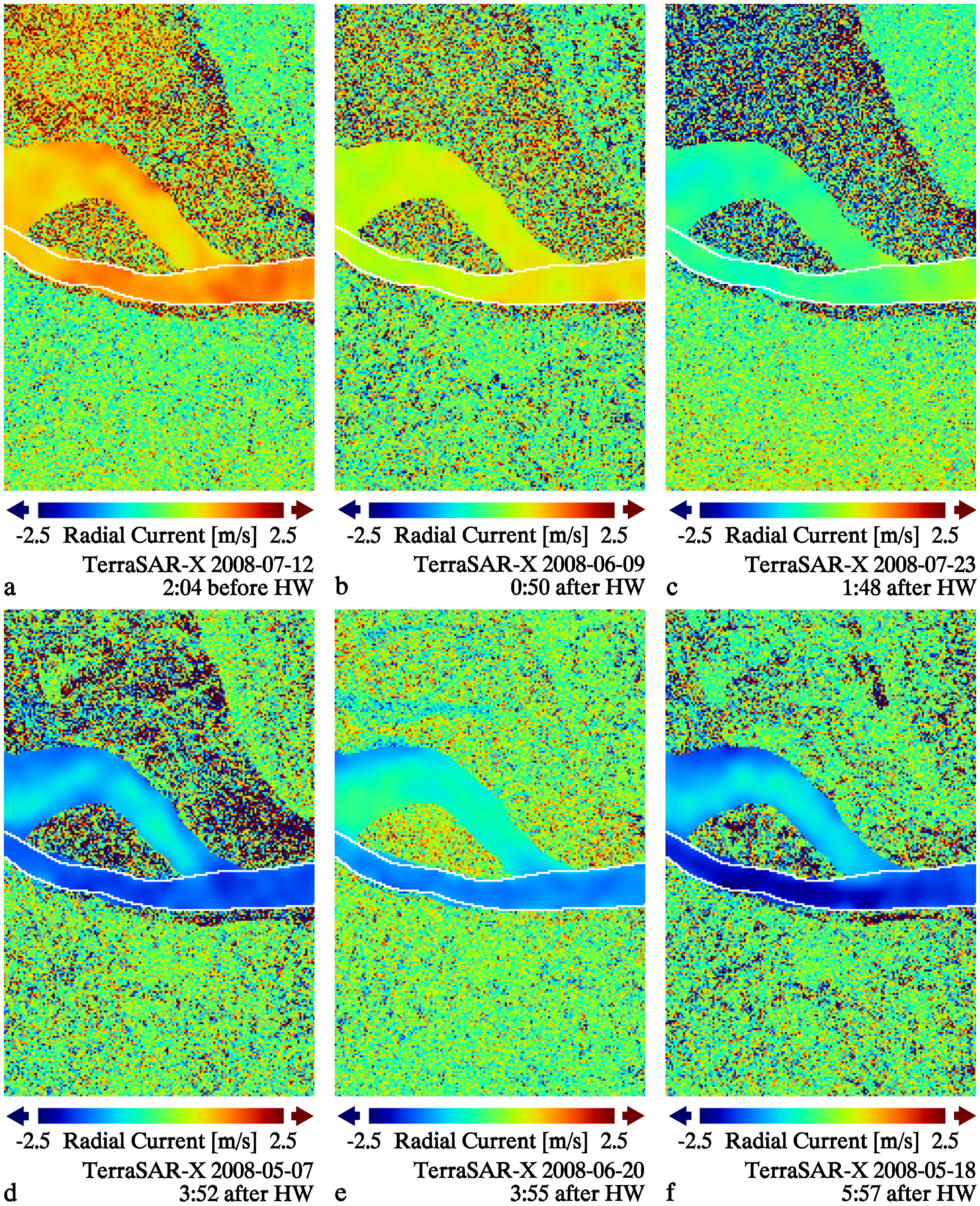


***Fig. 1: Line-of-sight surface current fields in the Elbe river as obtained for the six first test images from spring 2008 with the latest processing software. White lines indicate boundaries of the main test area for which statistical analyses have been carried out. Signatures over land show unfiltered zero-mean residual Doppler velocities. As a result of filtering, the current fields in the river look very smooth. Mean currents in the six cases range from about –1.9 to 1.3 m/s. Artifacts that were clearly visible in the first published versions of these images could be eliminated by optimizing filter parameters in the SAR raw data processing algorithm.***

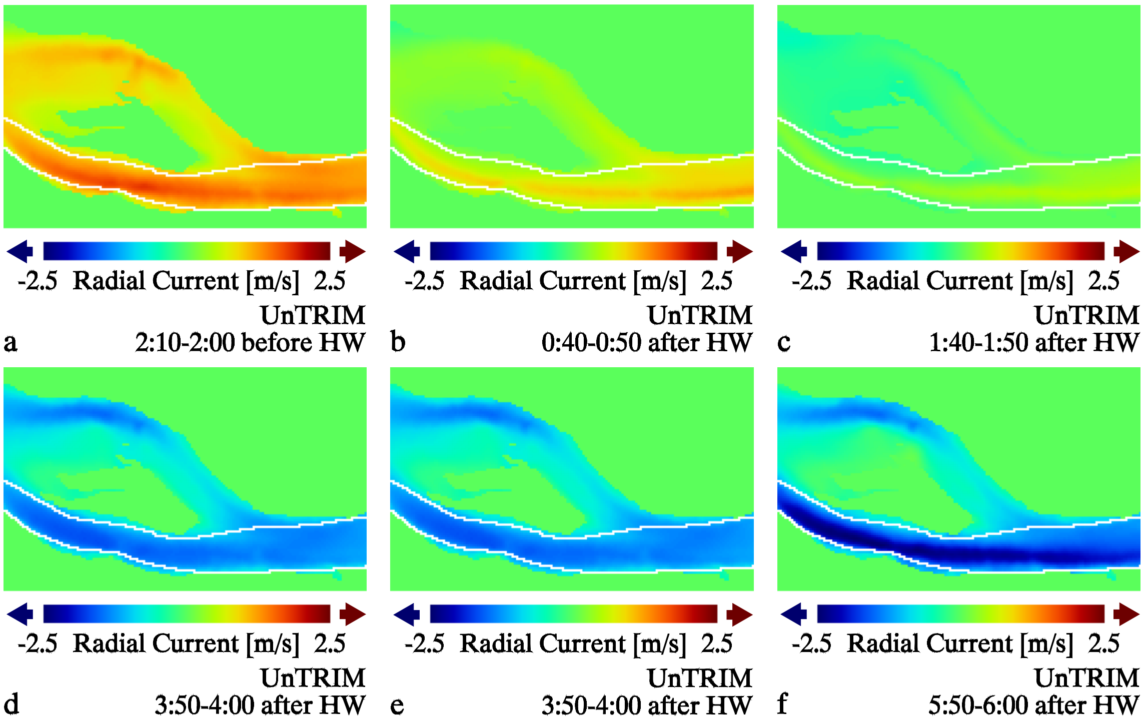


***Fig. 2: Line-of-sight surface current fields in the Elbe river according to numerical model UnTRIM of the German Federal Waterways Engineering and Research Institute (BAW), for six tidal phases corresponding to the tidal phases at the times of the TerraSAR-X overpasses. The current fields look similar to the ones obtained from TerraSAR-X.***

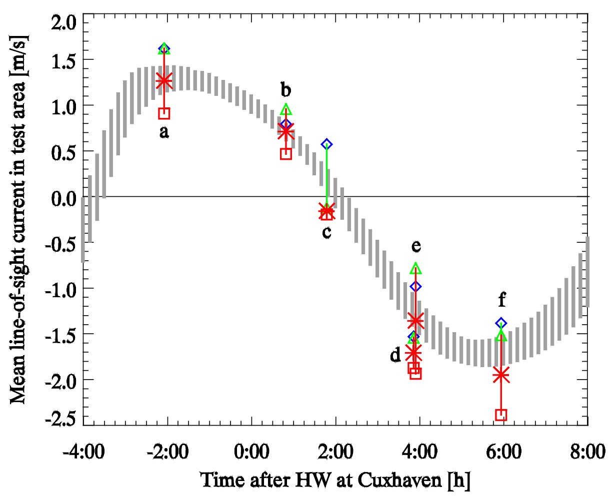


***Fig. 3: Diagram showing temporal variations of spatial mean line-of-sight currents in the mean test area as function of tidal phase, according to UnTRIM (gray bars) and TerraSAR-X. Blue diamonds show uncorrected Doppler velocities; green triangles show Doppler velocities after phase recalibration; red lines between triangles and red squares indicate theoretical maximum of corrections for wave contributions according to our model, and red asterisks show best estimates of mean currents after applying 50% of these corrections. The final results are in pretty good agreement with UnTRIM.***

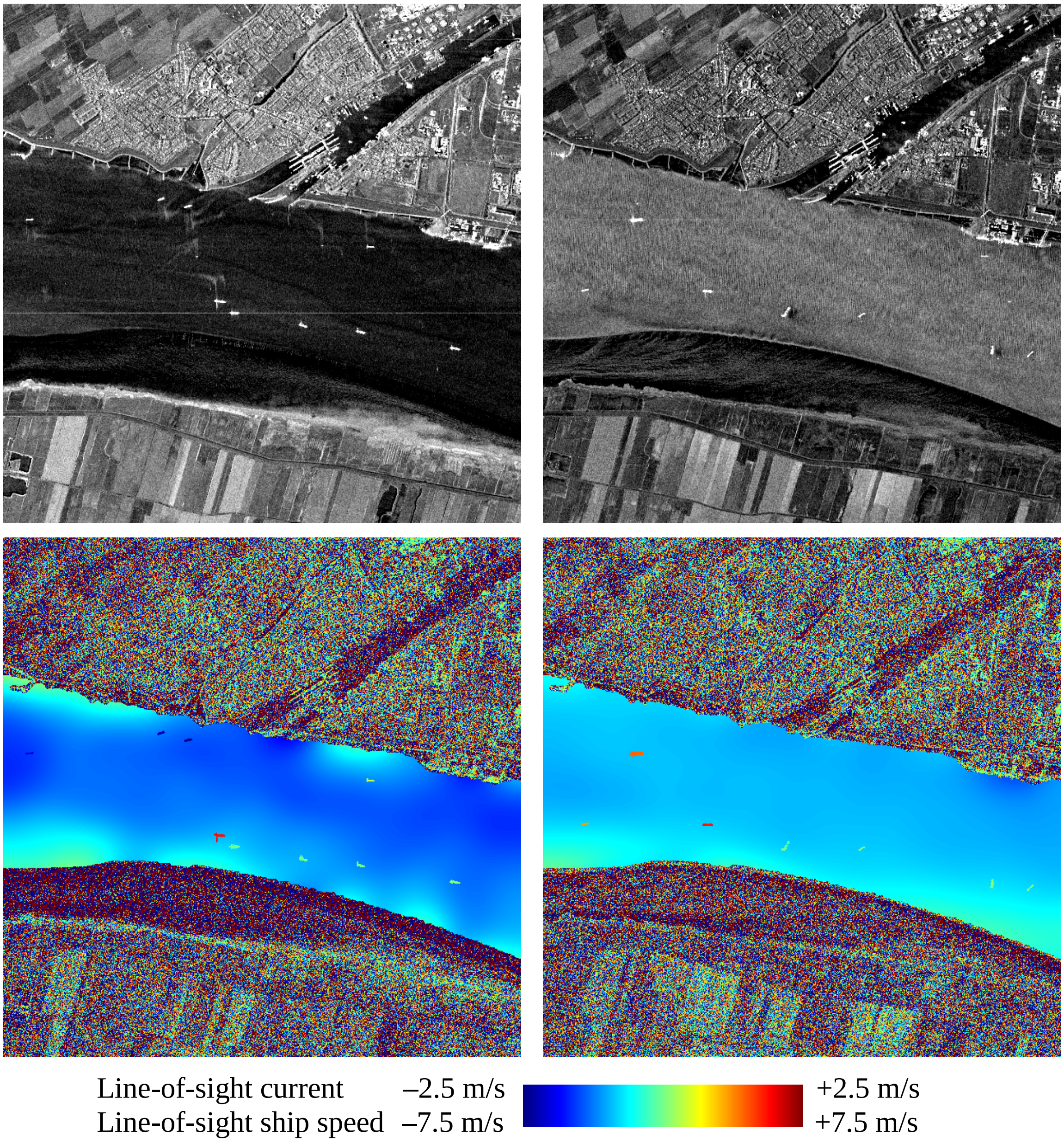


***Fig. 4: Two high-resolution SAR intensity images (top) and derived horizontal line-of-sight velocities (bottom) for a different part of the Elbe river where DRA-mode images were acquired in spring 2009. The velocity images are similar to the ones of Fig. 1, but the data quality is clearly better because of a higher original pixel resolution and a better overall data quality of DRA-mode data. These images were processed such that ships (bright spots in the intensity images) were included in the ATI data analysis; their speeds are shown with a different color coding. While the mean line-of-sight currents in these images are on the order of 1 to 2 m/s to the left, the line-of-sight speeds of 9 ships in the left and 7 ships in the right image range from about 7 m/s to the left to 7 m/s to the right.***